Short-Term Scheduling of Microgrids in the Presence of Demand Response

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Abstract—In this paper, operation management of microgrids is performed. To do so, some contingencies including outage of distributed generators (DG), energy storage (ES) and the upstream network are considered. Since the microgrids have suitable capabilities in terms of control and communication, demand response reserve can be applied to improve the operation management. Using Monte Carlo simulation method and Markov chain, several scenarios are generated to show the possible contingencies in various hours. Then, a scenario reduction method is used for reducing the number of scenarios. Finally, a two-stage stochastic model is applied to solve a day-ahead scheduling problem in mixed-integer linear programming by GAMS. Consequently, the effect of demand response in the reduction of operation cost is demonstrated.

Index Term—Demand response, microgrid, security-constrained unit commitment, two-stage stochastic programming.

I. NOMENCLATURE

Index (Set)

\( G \) \text{ DDGs and the maingrid index (set).}
\( H \) \text{ Hour index (set).}
\( S \) \text{ Scenario index (set).}
\( K \) \text{ Demand response blocks index (set).}
\( D \) \text{ Number of demand response providers.}

Binary variables

\( y_{g,h} \) \text{ ON (OFF) state of generator } g \text{ at hour } h \text{.}
\( u_{g,k} \) \text{ State of committed generator } g \text{ at point } k \text{.}
\( u_{g,h,r} \) \text{ Availability of generator } g \text{ at hour } h \text{.}
\( w_{g,h,r} \) \text{ Availability of energy storage at hour } h \text{.}
\( u_{d,h,k} \) \text{ Point } k \text{ of demand response } d \text{ at hour } h \text{.}
\( u_{d,h,r} \) \text{ Point } r \text{ of demand response } d \text{ at hour } h \text{.}

Parameters

\( P_{\text{Gmax}} \) \text{ Maximum (minimum) capacity of generator } g \text{.}
\( R_{\text{gmax}} \) \text{ Ramp-down (-up) rate of generator } g \text{.}
\( Bid_{g,h} \) \text{ Operation price of generator } g \text{ & market price.}

Variables

\( P_{\text{G}} \) \text{ Scheduled generation of generator } g \text{ at hour } h \text{.}
\( \text{Res}^{U(D)}_{g,h} \) \text{ Up- (down-) spinning reserve of generator } g \text{ at hour } h \text{.}
\( E_{g,h} \) \text{ Stored energy in storage at hour } h \text{.}
\( r_{g,h} \) \text{ Power charged (discharged) at hour } h \text{ in storage.}
\( \text{Res}^{U(D)}_{g,h} \) \text{ Deployed up- (down-) spinning reserve at hour } h \text{.}
\( \text{L Shed}_{h} \) \text{ Forced curtailed load.}
\( \alpha_{s} \) \text{ Probability of scenario } s \text{.}
\( EASDR_{d,h} \) \text{ Energy cost of demand response } d \text{ at hour } h \text{.}
\( ASDR_{d,h} \) \text{ Scheduled demand response } d \text{ at hour } h \text{.}
\( CASDR_{d,h} \) \text{ Capacity cost of demand response } d \text{ at hour } h \text{.}
\( ASDR_{d,h} \) \text{ Deployed demand response } d \text{ at hour } h \text{.}

\( Stup_{g} \) \text{ Startup cost of generator } g \text{ (DDGs).}
\( SuDo_{g} \) \text{ Shut down cost of generator } g \text{ (DDGs).}
\( cp_{g,h} \) \text{ Capacity cost of up- (down-) spinning reserve.}
\( ep_{g,h} \) \text{ Energy cost of up- (down-) spinning reserve.}
\( E_{\text{max}} \) \text{ Minimum (maximum) energy capacity of storage.}
\( P_{\text{Char.max(min)}} \) \text{ Maximum (minimum) power discharge capacity for storage.}
\( P_{\text{Dischar.max(min)}} \) \text{ Maximum (minimum) power charge capacity for storage.}
\( P_{\text{load,h}} \) \text{ Forecasted load at hour } h \text{.}
\( P_{\text{PV,h}} \) \text{ Forecasted PV generation at hour } h \text{.}
\( P_{\text{WT,h}} \) \text{ Forecasted WT generation at hour } h \text{.}
\( \eta \) \text{ Efficiency of charge/discharge of storage.}
\( PL_{h} \) \text{ Value of loss of load at hour } h \text{.}
\( CPI_{d,h,k} \) \text{ Capacity cost of point } k \text{ of demand response } d \text{.}
\( EPI_{d,h,k} \) \text{ Energy cost of point } k \text{ of demand response } d \text{.}
\( q_{d,h} \) \text{ Discrete demand response quantity } d \text{ at point } k \text{.}
\( \lambda_{d,h} \) \text{ Difference between two demand response blocks at hour } h \text{.}
II. INTRODUCTION

The concept of the microgrid was introduced to improve the distribution networks performance. Reducing the emissions, losses and operation cost as well as increasing reliability [1] are unique features of microgrids. Microgrids have suitable control facilities and communication systems including: Microgenerator Controller (MC) which controls active and reactive power of distributed generations (DGs), Load controller (LC) which controls loads by shedding when necessary and Central Controller (CC) which determines proper set-point of LC and MC for economic and safe operation [2]. Therefore, it is possible to schedule the microgrid operation using both demand side and supply management. Some papers studied about microgrid operation.

In reference [3], microgrid operation is optimized in two policies, first minimizing the cost and second maximizing the profit. Some of these optimization problems are solved by heuristic algorithms like particle swarm optimization [4]. For assessing the impact of contingencies the security studies in the microgrid are required [5]. With some changes, stochastic security-constrained unit commitment (SCUC) in the power system can be considered in the microgrid scheduling. In some papers, random disturbances are modeled as scenario trees using Monte Carlo Simulation (MCS) such as [6,7]. Unlike the deterministic SCUC, in the scenario-based method, each scenario has a probability which determines the weight of each contingency in the scheduling. Reference [8] used a stochastic single-stage stochastic model for unit commitment. A two-stage model was applied in [9] for stochastic SCUC in power systems, and this model with some changes was used for the microgrid in [10]. Moreover, a demand response model presented in [9] for demand side management in power system. Meanwhile, the role of responsive customers in electricity market among other players is evaluated in [11].

In this paper, we propose a model for short-term microgrid scheduling with demand side management. In fact, system uncertainties including outage of dispatchable distributed generators (DDGs), upstream network (maingrid) and energy storage system (ESS) are merged in a two-stage stochastic model for security assessment. Since demand side management is a suitable option in a smart grid for increasing the network reliability [1] are unique features of microgrids. Microgrids have suitable control facilities and communication systems including: Microgenerator Controller (MC) which controls active and reactive power of distributed generations (DGs), Load controller (LC) which controls loads by shedding when necessary and Central Controller (CC) which determines proper set-point of LC and MC for economic and safe operation [2]. Therefore, it is possible to schedule the microgrid operation using both demand side and supply management. Some papers studied about microgrid operation.

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Since this method needs to generate lots of scenarios, it is important to reduce the number of scenarios to cope with computational Burdon. Reduction methods are based on keeping essential features of original scenarios according to probability distances [16]. There are two methods to reduce scenarios in SCENRED2/GAMS including backward method and forward method [17]. The size of the stochastic program and required solution accuracy are effective for selection the proper reduction method [18].

B. Objective Function

For considering the security issues of the microgrid in an uncertainty environment, a stochastic two-stage optimization problem is formulated. This short-term stochastic operation management schedules the unit's energy and spinning reserve, simultaneously.

Analyzing the generated scenarios is implemented in the second stage to provide system security. The decision on unit's commitment state and their optimal generation and reserve second stage to provide system security. The decision on unit's commitment state and their optimal generation and reserve simultaneously.

The two-stage model is formulated as follows [18]:

$$\text{Cost} = \min \left[ \sum_{g} \left( \sum_{s} \left( P_{G,g,s} \cdot \text{Bid}_{g,s} + \text{Stup}_{g,s} + \text{SuDo}_{g,s} \cdot \text{z}_{g,s} \right) + \text{cp}_{g,s} + \text{dp}_{g,s} \cdot \text{Re}_{g,s} + \sum_{s} \text{CASDR}_{g,s} \right) + \sum_{s} \alpha \cdot \text{SEC}_{s} \right]$$

$$+ \sum_{g} \left( \text{EASDR}_{g,s} + \left( \text{P}_{s} \times \text{LShed}_{s} \right) \right)$$

(2)

The objective function is presented in equation (2), and the sum of spinning reserve procurement cost provided by DDGs and the maingrid, reserve procurement cost provided by demand response and forced load curtailment cost in each scenario $s$ is revealed in (3).

The constraints are as follows:

$$\sum_{g} P_{G,g} + P_{d,\text{sho},k} - P_{\text{sho},k} + P_{\text{w},k} + P_{\text{y},k} = P_{\text{load},k}$$

(4)

$$u_{g,k} + u_{g,k-1} = 1$$

(6-a)

$$P_{G,g} - u_{g,k-1} \leq R_{g}$$

(7-a)

$$0 \leq u_{g,k} \leq 1$$

(6-b)

$$P_{G,g} - P_{G,g,k-1} \leq R_{g}$$

(7-b)

$$0 \leq u_{g,k} \leq 1$$

(6-c)

For the first stage, equation (4) is used for balancing between loads and generation. Limitation of power generators is in (5). Status of start up or shut down of DDGs are specified by (6). Equation (7) is related to the ramp up/down constraints of units. Up/down reserve constraints of DDGs and the maingrid are in (8). For the second stage, (9) is related to balancing between loads and all power generation and imported power in scenario $s$ and (10) is up/down reserve constraints of DDGs and the maingrid in scenario $s$. Constraints related to demand response in scenarios are in (11). Accordingly, demand response in each scenario must be lower than scheduled demand response and also energy cost of demand response is considered in the second stage instead of capacity cost.

V. CASE STUDY & NUMERIC RESULTS

A. Case study

The data of DDGs are presented in Table I. The maingrid can import/export power until 500 kW to/from the microgrid. The failure rate of the main grid is 0.0091 $f$ / hr , mean time to return connected mode is 30 minutes. Figure 2 shows the cost of DDGs production and market clearing price at each hour. 30% and 100% of units’ production cost and maingrid are considered as energy cost of up- and down-spinning reserve.

<table>
<thead>
<tr>
<th>Table I</th>
<th>SPECIFICATION OF DDGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>Min. Power (kW)</td>
</tr>
<tr>
<td>MT 1</td>
<td>20</td>
</tr>
<tr>
<td>MT 2</td>
<td>20</td>
</tr>
<tr>
<td>FC 1</td>
<td>10</td>
</tr>
<tr>
<td>FC 2</td>
<td>10</td>
</tr>
</tbody>
</table>
The studied network is in Figure 1 which includes two microturbines, two fuel cells, two wind generators, a PV generator and an energy storage system. Maximum energy of the energy storage system is 180kWh and maximum power charge and discharge for storage is 150kW which its efficiency is 85% for both. Wind generator data and PV plant data are in Table II and all data of the given microgrid are in reference [18]. In this paper, three cases are studied for assessment of proposed scheduling model. The first case is stochastic short-term scheduling of microgrid without the presence of demand response. In the second case, case 1 with the presence of demand response is scheduled to show the effect of demand side management in the microgrid scheduling. In the third case, the prices of ADSR are dropped. Horizon time of these studies is 12 hours. Scheduling of two cases is performed as MIP by CPLEX solver in GAMS. It is solved with the processor of 2.4GHz and 6 GB RAM in less than 1 second.

**B. Numeric results**

1) Case 1

In case 1, stochastic SCUC is performed. Uncertainties of DDGs, ES, and the maingrid are considered. Ten thousand scenarios with equal probabilities by MCS are generated. Scenarios consist of a vector of 6 stochastic variables which all of them are binary and related to units’ availability. Afterward, scenarios are reduced to 10 scenarios with new probabilities by SCENRED2 solver in GAMS.

![Figure 1. Sample microgrid](image)

**TABLE II. PV AND WIND GENERATORS DATA**

<table>
<thead>
<tr>
<th>Solar generator</th>
<th>Open circuit Voltage (V)</th>
<th>Voltage temperature coefficient (V/°C)</th>
<th>21</th>
<th>0.088</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short circuit Current (A)</td>
<td>3.4</td>
<td>Current temperature coefficient (A/°C)</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>Voltage at maximum power (V)</td>
<td>17.4</td>
<td>Nominal operating temperature(°C)</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Current at maximum power (A)</td>
<td>3.05</td>
<td>Ambient temperature(°C)</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind Turbine</th>
<th>Cut-in speed (m/s)</th>
<th>Cut-out speed(m/s)</th>
<th>3.5</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated wind speed (m/s)</td>
<td>12</td>
<td>Rated power (kW)</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

To reduce the response time of the scenario reduction program, a forward reduction method is used. Consequently, Scenario reduction process lasts about 30 seconds for each hour. The scheduling problem is solved in the microgrid optimization module by offered stochastic scheduling model in linear MIP under CPLEX. Unit commitment result is presented in Table III. As expected, units with low production cost have first priority for commitment. Also, when the market price is low whole feasible capacity of maingrid is imported to the microgrid to supply inside loads and charge energy storages. When the market price is high, all DDGs are committed to maximum capacity and the energy storage is discharged to sell the surplus power to maingrid.

This stochastic scheduling, as mentioned in [10], is very useful for reduction operation cost because the reserve capacity is scheduled according to security system requirements through contingencies analysis. In spite of conventional ways, scenarios determine all possible events and states with their probability and objective function makes the final decision by analyzing them.

2) Case 2 & Case 3

In the second case, ASDR is added to scheduling based on the model introduced in section III. ADSR, in this paper, consists of 4 blocks which capacity cost and energy price as shown in Table IV would be assigned to it.

![Figure 2. Production cost of DDGs and market price.](image)
### Table III: Unit Commitment Results of Case 1

<table>
<thead>
<tr>
<th>Hour</th>
<th>MT1 (kW)</th>
<th>MT2 (kW)</th>
<th>FC1 (kW)</th>
<th>FC2 (kW)</th>
<th>Maingrid (kW)</th>
<th>ES (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>147.1</td>
<td></td>
<td></td>
<td></td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>340</td>
<td>10</td>
<td>0</td>
<td>500</td>
<td>-150</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>350</td>
<td>10</td>
<td>0</td>
<td>500</td>
<td>-60.8</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>290.9</td>
<td>100</td>
<td>50</td>
<td>500</td>
<td>-0.8</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>400</td>
<td>300</td>
<td>100</td>
<td>-189.6</td>
<td>110.6</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>400</td>
<td>300</td>
<td>150</td>
<td>-306.4</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>400</td>
<td>400</td>
<td>300</td>
<td>150</td>
<td>-373.1</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>400</td>
<td>300</td>
<td>150</td>
<td>-252.8</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>400</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>-45.6</td>
</tr>
<tr>
<td>10</td>
<td>150</td>
<td>400</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>75.31</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>400</td>
<td>100</td>
<td>0</td>
<td>400</td>
<td>-2.6</td>
</tr>
<tr>
<td>12</td>
<td>150</td>
<td>228.8</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Table IV: Demand Response Data

<table>
<thead>
<tr>
<th>Case</th>
<th>k</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>qb$_k$ (kW)</td>
<td>$25%$ of total response</td>
<td>$50%$ of total response</td>
<td>$75%$ of total response</td>
<td>$100%$ total response</td>
</tr>
<tr>
<td>2</td>
<td>0.035</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>0.13</td>
<td>0.14</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

In the third case, the prices are less than the first case to demonstrate the effect of DR price on total operation cost and DR scheduling. The total amount of DR is 60 kW. According to economic and security requirements, each block can be reserved at each hour. Unit commitment results are presented in Figure 3.

As can be seen in the second case, 45kW demand response reserve is scheduled at hour 10 and causes a decrease in total operation cost compared with case 1 according to Table V. Moreover, after running case 3, due to the lower price of DR block price, more DR reserve scheduled at hour 5, 6, 7, 8 with 30, 30, 30 and 15 kW. Meanwhile, the total operation cost is reduced as well.

### Table III: Total Operation Cost Case 1 & 2

<table>
<thead>
<tr>
<th>Case</th>
<th>Operation Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas1</td>
<td>1241.01</td>
</tr>
<tr>
<td>Case2</td>
<td>1224.9</td>
</tr>
<tr>
<td>Case3</td>
<td>1219.6</td>
</tr>
</tbody>
</table>

### VI. Conclusions

Flexible loads are proper means to not only reduce the operation cost of a microgrid, but also to increase the system capacity. In this paper, in addition to using a stochastic model for economic dispatch and unit commitment, an ASDR has been applied to increase system reliability and security along with a decrease in total operation cost. A scenario-based contingencies analysis has been performed to extract possible events like outage of DDGs, ESs and the maingrid. A two-stage stochastic SCUC has been employed in such a way that final decisions including power generation scheduling and reserves are made in the first stage through contingencies analysis in second stage with minimizing the total operation cost in mixed-integer linear programming (MILP). Results show that ASDR caused a decrease in total operation cost. Likewise, the load curve is shaved in peak hours. Moreover, with decreasing the DR Price, in addition to a drop in total operation cost, more DR capacity is scheduled. In other words, the less cost for DR Price is considered, the more DR scheduling and less total operation cost will be taken place.
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